Hybrid Bayes/GLRT Signal Detection

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LONG TERM GOALS

Develop a new and simple scheme to detect short-duration underwater signals. Present methods tend to be overly complicated and/or too finely tuned to one type of signal. The proposed technique uses a Bayesian approach with “hyper”-parameters, meaning that the model can adapt itself to a wide range of possible signals and signal types.

OBJECTIVES

Obtain a new formulation of the GLRT that avoids enumeration and is computationally feasible by replacing intractable enumeration over possible signal characteristics with an a priori signal distribution, and by estimating the hyperparameters (of the prior distribution) jointly with other signal parameters, it is possible to It turns out that this estimation can be done very efficiently and neatly via the estimation-maximization (EM) algorithm.

This approach relies on a coherent statistical model, and is easily and rationally extended in a number of different directions, such as using assumptions of energy contiguity in time and frequency. The objectives are to realize these extensions, and to compare their performance with existing transient detection algorithms.

APPROACH

Difficulties arise with the GLRT (generalized likelihood ratio test) in situations where one or more of the unknown signal parameters requires an enumeration that is computationally intractable. In the transient signal detection problem the frequency characteristics of the signal are typically unknown, so even if an aggregate signal bandwidth is assumed, the estimation problem intrinsic to the GLRT requires an enumeration of all possible sets of signal locations within the monitored band. In this project, a prior distribution is imposed over those portions of the signal parameter space that traditionally require enumeration. By replacing intractable enumeration over possible signal characteristics with an a priori signal distribution, and by estimating the hyperparameters (of the prior distribution) jointly with other signal parameters, it is possible to obtain a new formulation of the GLRT that avoids enumeration and is computationally feasible. It turns out that this estimation can be done very efficiently and neatly via the estimation-maximization (EM) algorithm. The GLRT philosophy is not changed by this approach -- what is different from the original GLRT is the underlying signal model. The performance of this new approach appears to be competitive with that of a scheme of emerging acceptance, the “power-law” detector of Nuttall. Further, the approach relies on a coherent statistical model, and is easily and rationally extended in a number of different directions, such as using assumptions of energy contiguity in time and frequency.

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This research had its genesis in Nuttall's modeling of transient signals having "unknown location, structure, extent, and strength", as a perturbation in the DFT domain away from the independent and identically-distributed exponential random variables arising from an assumption of a white and Gaussian time-domain ambient process. This simple and excellent observation gave rise to a series of "power-law" detectors, basically using test statistics based on summing the DFT magnitude-squares raised to powers in the range of 2-3. While we recognize the elegance of such a statistic, the approach here is to apply the model as faithfully as possible, and to derive the *optimal* detector. The original approach can be summarized as follows. Consider that DFT samples are exponentially-distributed with one of two (unknown) scale parameters; and further, allow the process controlling which of these is active for each DFT sample to be a Bernoulli process (with unknown parameter). If these (three) parameters can be estimated accurately – and using the EM approach, they can be – then an optimal detector can be constructed.

More recent approaches include modeling as more than two families of exponentials, and a generalization of the Bernoulli process to a hidden-Markov model (HMM). We have further examined the use of EM as a basis, and have determined that under some circumstances a more-sophisticated maximization algorithm can offer faster, and sometimes better, convergence. We have also explored modifications on the model to mitigate the statistical problem of a "point-null" hypothesis.

Finally, we have developed, characterized, and successfully tested a test based on the "mean-value dispersion" statistic, essentially the ratio between the geometric and arithmetic means of the DFT data. It turns out that this statistic has an elegant derivation based on the new statistical concept of "overdispersion" of a one-parameter exponential family. More important, this statistic performs extremely well in cases that the ambient noise power is unknown – that is, in constant false-alarm rate (CFAR) operation.

Those most intimately involved with the project include Peter Willett (the PI), Biao Chen (a PhD student at the University of Connecticut), and Dr. Roy Streit (from NUWC, Newport) who has a parallel contract from ONR on the same topic. More peripherally, another University of Connecticut graduate student Zhen Wang is testing these algorithms against a wide class of competitors on time-domain (rather than directly simulated in the frequency domain) data for an application on another project; and Thialingam Kirubarajan, a University of Connecticut post-doctoral student, is exploring competitor algorithms to EM.

WORK COMPLETED

With respect to the <u>basic EM approach</u>, we offer:
The discrete Fourier transform of a block of data containing only white Gaussian noise gives rise to a uniform set of exponential variates, while an additive short-duration signal has the effect of destroying this uniformity. One of the best known ways to recognize such a deviation from uniformity is the power-law detector, particularly if the power is chosen with care to match an assumed transient signal bandwidth. We have pursued a different approach: a GLRT whose estimation is over a set of hyperparameters describing the nonuniformity, and whose computation relies on the EM algorithm. In its original formulation these hyperparameters dealt with an assumed underlying Bernoulli signal/no-signal model, but we have extended it to incorporate multiple signal levels, CFAR operation, and a

hidden-Markov signal-contiguity model. We have demonstrated that our approach has performance comparable to and often exceeding that of the best power-law detector. We have also described a modified Bayes/GLRT detector which specifies that the total energy of the transient must exceed a certain level in order to have a non-trivial transient detection. Numerical results show that the new method does provide some performance improvement given that the threshold is appropriately chosen.

With respect to the mean-value detector, we offer:
We have proposed a statistic for testing homogeneity of a data set which assumes exponential distribution under the null hypothesis. This is derived as the generalized likelihood ratio test of "overdispersion" in a doubly-exponentially distributed data set. Some properties of this statistic revelant to the transient detection task have been summarized, and include its CFAR nature, its provenance, and both its simulated and analytical (approximate) performance. This latter is in general a considerable improvement over the CFAR version of the power-law detector.

RESULTS

A manuscript on the basic approach has been submitted to IEEE Transactions on Signal Processing, and a reasonably favorable review returned; a revised paper has been submitted. In addition to discussion of the basic model above, extensions to the case of multiple-level transients (i.e. the bin-occupancy process is not simply binary, but P-ary), to heavy-tailed distributions, and to the augmentation of the Bernoulli process to be a hidden Markov model (HMM) to capture bandwidth contiguity structure, are all dealt with in the manuscript. One interesting outcome here was that the while the performance of the new approach as tested on "transient" signals simulated directly in the frequency domain was comparable to that of the (best) power-law detector, when the transients were simulated in the time-domain (as bursts or tonals of varying kinds) the new approach was much more effective. Upon further examination it appears that this is due to the tendency of such transient signals to "split" their energy into two roughly equal populations in the frequency domain, a situation very favorable to the new approach.

An arguable problem with the model is that it is "point-null"; that is, while the alternative is composite, the null hypothesis of all-ambient bins has less freedom. The result is to some extent a favoring of the alternative, leading to the necessity of a relatively high threshold value for given false-alarm rate performance. As remedy, we have explored modification of the EM procedure to deal with an inequality constraint on the parameters, specifically that the estimated signal-to-noise ratio (SNR) be larger than a constraint value. The results, as reported in the Proceedings of the 1998 Conference on Information Sciences and Systems (CISS), indicate that there is indeed performance improvement, but that this improvement is not unduly large.

We have also explored the underlying exponential model from a somewhat different point of view. Specifically, we have applied the relatively new statistical concept of "overdispersion" to test whether or not all exponential random variates come from the same population. The result, derived (we hope) neatly and mathematically, is a detector which uses a logarithmic nonlinearity, the statistic being alternatively expressible as the ratio of the arithmetic to geometric means of the magnitude-square FFT data. The resultant test is CFAR, and the performance appears to be impressive. Some results about this were reported in the Proceedings of the 1998 Conference on Information Sciences and Systems. A more comprehensive journal paper, include much performance analysis, will be submitted to IEEE Transactions on Signal Processing within a month.

IMPACT/APPLICATIONS

This research is most directly applicable to the passive sonars, and in particular to the automatic detection of short-duration (transient) signals with deployable arrays of sensors. The eventual goal is to have a reliable and high-performance system capable of monitoring simultaneously several hundred array channels (beams) for possible transient activity. If activity is detected, it is expected that this information will be passed to a higher-level *classification* system, and thence if a threat is adjudicated to a human operator for verification.

TRANSITIONS

No transitions from this theoretical research to the fleet are expected soon.

RELATED PROJECTS

The principal investigator on this project works closely with the Transient Signal Processing group at NUWC, Newport, and collaborates closely with Stephen Greineder, Tod Luginbuhl, and Paul Baggenstoss of that section. Between the PI and that group there have been a series of contracts (recently N66604-96-C-0553 and N66604-97-M-3139) on the detection of transient signals, most particularly on the use of the Page test with and without a hidden Markov model underlying assumption. The results above on the mean-value dispersion detector were derived in consultation with the above personnel, and the latter contract is given joint credit in its publication.

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PATENTS

None.